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Theoretical SIS Mixer Research

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I. Summary

Theoretical research has been conducted to elucidate the basic physics behind the properties of superconductor-insulator-superconductor (SIS) tunnel junction receiving devices. The properties of SIS mixers using nonideal junctions and finite LO power, were determined by analytic expansion of the equations of the quantum theory of mixing, and also by computer simulations of SIS receivers over the entire range of experimental parameters. The result is a new coherent and intuitive picture of SIS mixer behavior. Many of the outstanding mysteries and questions about SIS receivers are resolved, and this contributes greatly to the design and interpretation of SIS mixer experiments. Other calculations show how to achieve sub-quantum noise temperatures in the phase sensitive SIS mixer, an important step towards realization of ultra-low-noise detectors. A simplified model casts doubt on the superlative experimental results reported for the rf-series dc-parallel biased array SIS mixer.

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13. ABSTRACT *(Maximum 200 words)*

Theoretical research has been conducted to elucidate the basic physics behind the properties of superconductor-insulator-superconductor (SIS) tunnel junction receiving devices. The properties of SIS mixers using nonideal junctions and finite LO power, were determined by analytic expansion of the equations of the quantum theory of mixing, and also by computer simulations of SIS receivers over the entire range of experimental parameters. The result is a new coherent and intuitive picture of SIS mixer behavior. Many of the outstanding mysteries and questions about SIS receivers are resolved, and this contributes greatly to the design and interpretation of SIS mixer experiments. Other calculations show how to achieve sub-quantum noise temperatures in the phase sensitive SIS mixer, an important step towards realization of ultra-low-noise detectors. A simplified model casts doubt on the superlative experimental results reported for the rf-series dc-parallel biased array SIS mixer.

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II. Research Objectives

The research objectives set forth in the proposal leading to this grant are the following:

1. The first objective of this research is to conduct a careful and exhaustive analytical examination of the quantum theory of mixing, and of its predictions of superconductor-insulator-superconductor (SIS) mixer behavior.
2. The second objective of this research is to understand the properties of SIS mixers having very broad input bandwidth.
3. The third objective of this research is the delineation of the noise predictions of the quantum theory of mixing and a careful study of SIS mixer noise.
4. The fourth objective of this research is to analyze the excess noise of arrays of SIS junctions.
5. The fifth objective of this research is to study the limitations of SIS mixers at higher frequencies, close to and exceeding the energy gap frequency of the superconductors used.
6. The sixth objective of this research is to begin working towards the realization of a large array of planar-antenna-coupled SIS direct detectors.

III. Research Accomplishments

The research performed under AFOSR Grant #90-0316 set the stage for the emergence of a new coherent and intuitive picture of SIS mixer behavior. It appears that most if not all important aspects of SIS mixer operation can now be understood in a simple and straightforward manner. (It must be noted that this major undertaking is not yet complete.) Although most of the synthesis of this new picture was formulated in the last twelve months, after the funded period of this grant, these results will be described here as the outgrowth of the grant research. Section A below is early work which forms the groundwork for most of what followed. Section B describes our new picture of SIS mixer behavior.

Thus, significant progress was made towards achieving many of the above research objectives. In the following description of research accomplishments, the numbers in square brackets refer to the publications listed below in Sec. IV.

A. Near-ideal SIS mixer

Under a previous AFOSR grant we examined the noise properties of an SIS mixer with finite LO power using a slightly nonideal junction, using the small α approximation ($\alpha \equiv eV_{LO}/\hbar\omega$ is the reduced LO voltage across the junction). We found that the increase in the minimum added-noise temperature over the quantum limit $T_Q = \hbar\omega/2k$ is given by $\delta T_Q = (\hbar\omega/k)\sqrt{I_0 I_2}/I_1$; this minimum requires that α be given by $\alpha^2 = 8\sqrt{I_0/I_2}$. ($I_n$ is the current measured on the unpumped I-V curve of the junction at voltage $V_0 + n\hbar\omega/e$.)

During the present grant period this research has been much expanded, completed, and published [3]. In order to determine the limitations of the small α approximation, we examined the complete equations of the quantum theory of mixing in the "three-frequency" low-IF approximation keeping terms to order α^6. We found the remarkable result that the small α approximation works up to and beyond $\alpha = 1$ for a DSB mixer, because the higher order terms almost vanish! This explains why the small α approximation has given certain reasonable results in the past, even though real mixers always work at $\alpha \approx 1$. However, the small α approximation should not be very successful in describing the SSB SIS mixer, for which the higher order terms are considerable.

Our results clear up several other mysteries. The leakage current at the bias point, I_0, is the crucial parameter in determining the minimum mixer noise. (But see item B.1, below.) It is also the crucial parameter in determining the optimum rf bias point: even an infinitesimal I_0 forces α to be of order unity. Therefore, although an SIS mixer using an *ideal* junction can reach the quantum noise limit only in the limit of zero LO power, even the most nearly ideal junctions made today require a considerable LO for best sensitivity. This is the reason why all SIS mixer experiments operate with $\alpha \approx 1$.

We also used the same approach to investigate the conversion gain of the near-ideal SIS mixer. We found that while the available conversion gain of an SIS mixer is strongly influenced by the *slope* of the I-V curve at the bias point, the actual conversion gain for power delivered into a finite load admittance is largely independent of modest nonidealities. This leads us to the controversial prediction that the conversion gain using any reasonably good quality SIS junction is essentially equal to that using a perfect junction.

The calculations performed in this work are unique in that they employ the complete equations of the quantum theory of mixing in the three-frequency, low-intermediate-frequency model, making no simplifying approximations. The success of this work has prompted several researchers to attempt to use the same techniques in their own research. Note that our research delineates the limitations of the widely employed small LO power approximation.

B. Emergent properties of optimized SIS receivers

It is a straightforward computation to predict the range of behavior of SIS mixers using quantum mixer theory once the relevant parameters have been chosen, and several researchers have made such calculations. But choosing appropriate values for the many parameters requires considerable judgment, and these calculations have generally made restrictive assumptions and have been of little use to other workers in this field. The paradoxical result is that although the quantum mixer theory is generally believed to offer a complete description of SIS mixing, the theory has *not* provided a coherent and intuitive picture of SIS mixer behavior. Although the theory has proven useful in the *interpretation* of experimental SIS mixer results, it has been of little use in the *design* of SIS mixer experiments. Nobody really has had a good feel for how SIS mixers work.

Our goal was to remedy this situation. The research described in Sec. A was helpful, but much of the experimental parameter space is not accessible to neat analytic calculation. In order to gain an intuitive understanding we decided to use the quantum mixer theory for computer simulations of SIS receivers over the entire range of experimental parameters (frequency, embedding impedances, junction characteristics, etc.). Only two restrictions were imposed. First, we considered only "optimized" receivers, for which the receiver noise temperature is minimum for a given choice of parameters. This of course is the experimentally interesting

situation. Second, we required that the signal reflection gain and the signal to image conversion gain should both be small [9,14]. This unusual restriction turned out to be perfectly justified -- the high reflection solutions are not experimentally accessible -- but also we found that this restriction was necessary in order to get comprehensible results. This may be the most important distinction between ours and previous work.

We accumulated vast files of computer data for various parameter values, and yet, this project is still not completed. Nevertheless, various trends in our results point to significant behavior, some of which is surprising and certainly unexpected. Although the quantum mixer theory predicts a wide range of possible behavior for SIS mixers, narrowing our attention to only optimized receivers allows us to identify the "emergent properties" of SIS receivers and to formulate a coherent description of SIS mixer operation, which is now briefly presented.

There are four fundamentally distinct types of noise which are important in SIS receivers: 1) the uncorrelated mixer noise, which arises from the leakage current shot noise of the SIS junction; 2) the LO-induced shot noise, which may be called "correlated" noise because it is conventionally represented by correlated noise sources placed at the mixer's signal, image, and IF terminations; 3) the thermal noise incident upon the signal and image ports of the mixer; and 4) the noise due to the (well-isolated) IF amplifier, including thermal noise from the isolator reflected by the IF port of the mixer. Noise component 4 can be considered together with noise component 1, because to first approximation their parameter dependencies are the same. Note that quantum noise is not listed; depending on the situation, quantum noise appears as part of noise components 1, 2, and 3. For the most common case of a double sideband (DSB) mixer, with equal signal and image source impedances, the thermal noise component 3 is most conveniently ascribed to the signal source and not to the receiver itself.

This leaves two separate kinds of noise, the correlated LO-induced shot noise and the uncorrelated noise. It is easy to show that in order to minimize the receiver noise temperature the mixer operating parameters must be adjusted so that these two components are roughly equal [10]. Since the uncorrelated noise occurs at the output of the mixer, this requires a trade-off between the mixer correlated noise temperature, specified at the input of the mixer, and the mixer gain. The mixer correlated noise can be cancelled by an appropriate choice of operating parameters; this occurs when the LO is perfectly impedance matched to the mixer. However, the mixer correlated noise increases rapidly as the parameters are varied away from cancellation. The mixer gain, on the other hand, is given by a simple impedance matching formula, and so it is a very slow function of the parameters. Therefore, the receiver is optimized for parameters quite close to LO match, and this is far from signal match or maximum gain.

The picture of SIS receiver operation sketched here is simple, straightforward, intuitive, and very different from the standard view (which is a adaptation from Schottky mixers). Most of the results have been embodied in simple equations derived from intuitive considerations. A few of the many new implications of this picture are now listed [8-11,14]:

1. The output noise temperature, rather than the standard input noise temperature, is the fundamental measure of the shot noise of the SIS mixer.
2. The leakage current of the SIS junction is important only if its "temperature" is larger than the noise temperature of the IF amplifier. Otherwise, the IF amplifier noise dominates receiver dynamics. The output noise temperature of an optimized receiver is twice the sum of these temperatures.
3. A simple first strategy for SIS receiver optimization is to improve the LO match.

4. The nonlinear quantum susceptance is not important to the operation of optimized SIS receivers. It is merely one factor to be considered in achieving an LO match.

5. It is not advantageous to attempt to achieve high gain from an SIS mixer. Rather, a moderate, unity to 10 dB, gain gives best receiver performance.

6. It is not advantageous to attempt to use IF transformers to achieve an output match. This increases the receiver noise temperature.

7. The quantum theory of mixing will always predict considerably higher conversion gain for high quality SIS junctions than can actually be achieved in experiment.

8. In general, the best noise temperatures for SIS receivers reported in the literature will be about twice the respective mixer noise temperatures.

9. The output noise temperature of an optimized receiver is independent of frequency up to twice the superconducting energy gap frequency. Thus there is no intrinsic impediment to the realization of supra-THz SIS receivers using Nb-based junctions.

10. The widely quoted and stringent constraint, that for high frequency SIS mixers the junction critical current density should increase as frequency squared, is not true. Rather, the choice of junction size and current density for submillimeter-wave SIS mixers is not sharply prescribed and should be made on purely technological grounds.

11. Measuring of the noise temperature of the rf input section of an SIS receiver now generally takes several man-days. It is possible to use a simple hot/cold-load technique to determine this quantity in minutes, to much greater accuracy.

It is clear that our new synthesis, a description of SIS mixer behavior, contributes greatly to the design and interpretation of SIS mixer experiments. In addition, many of the outstanding mysteries and questions about SIS receivers are resolved. This work is far from complete, and we sense that other significant results are likely. We hope to have the opportunity to pursue this to completion.

C. The phase sensitive SIS mixer

The conventional SIS mixer has a minimum added-noise equivalent temperature of 1/2 photon (in proper units). This quantum noise is a result of the Heisenberg uncertainty principle prohibition of a perfect simultaneous measurement of the two quadratures of an electromagnetic wave incident on the mixer. One way to avoid this quantum limit, and achieve less added noise, is to perform a measurement of only one quadrature in such a way that all information about the other quadrature is lost. This is the rationale of the phase sensitive SIS mixer, which employs two local oscillators equally spaced about the signal frequency.

Previous to our work, analytic calculations of the phase sensitive SIS mixer were severely limited in scope, assuming the weak LO limit, shorted image frequencies, and ignoring reactances. This approximation guaranteed infinite IF mismatch and zero conversion gain. These calculations found a minimum noise temperature of 1/8 photon. Although this factor of four decrease in noise temperature appears to be a considerable improvement, there is no real noise suppression: the noise in the detected quadrature remains the same as in the conventional case, while the signal contributions from the two LO's add coherently. Previous numerical calculations, on the other hand, found noise temperatures of $< 1/8$ photon, but without an understanding of what factors lead to lowest noise in the extremely broad parameter space.

During this report period we performed new analytic calculations of the phase sensitive SIS mixer [12]. We allowed arbitrary complex termination admittances at all ports, which allowed finite conversion gain. This calculation is much more general (and much more laborious!) than the earlier one. The main approximations are the weak LO limit and the assumption of ideal junctions.

We found that the minimum noise temperature of the phase sensitive SIS mixer is zero. The noise temperature is zero when and only when there is infinite gain. This result is physically realistic and reassuring; it means that the output noise is a smooth (non-zero) function. It is interesting to note that we found that the minimum noise temperature is exactly 1/8 photon if the signal is perfectly matched into the mixer. Thus some signal port reflection is essential in order to have any noise cancellation. We still don't understand why.

Our results are intuitively reasonable. Before it was difficult to find any noise cancellation in the numerical calculations (and impossible in the analytic calculations). These results show the way. This is an important step towards realization of ultra-low-noise SIS detectors.

D. Rf-series dc-parallel biased arrays for SIS mixing

For the Josephson junction oscillator it is advantageous to supply the dc current in parallel for junctions which are in a series linear array for the rf currents. This design has been adapted for the SIS mixer [A.B. Ermankov V.P. Koshelets, S.A. Kovtonyuk, and S.V. Shitov, "Parallel biased SIS-arrays for mm wave mixers: Main ideas and experimental verification," IEEE Trans. Magnetics MAG-27, 2642 (1991); and many other papers by the same group] and many similar advantages are claimed. Most striking are the superlative experimental results reported in this paper: An SSB receiver noise temperature of 5 K at 47 GHz with 10 dB gain, wide instantaneous bandwidth, and high dynamic range. Such results should revolutionize SIS mixers, and indeed several U.S. groups have undertaken similar research.

And yet many questions remain. The excellent experimental results are apparently not simultaneously achievable. The mixer appears to be very sensitively dependent on external tuning, which is surprising for the low relative capacitance SIS junctions used. The output IF power is not smooth but has numerous small features as a function of dc bias voltage, utterly unlike conventional low frequency SIS mixers.

We have endeavored to analyze the rf-series dc-parallel biased 2-junction SIS array. The analysis in the cited reference assumes that the two junctions work in tandem: that the dc current and the rf voltage divides evenly between the two junctions. To decide whether this is in fact true, we simplified the problem by studying this circuit containing two identical symmetrical classical switches. We find that each junction approximately switches on and off each half cycle, out of phase with each other. This would predict that the photon-induced step on the I-V curve should be divided in half, and this is in fact evident in the cited reference. However, we also find that the switching point is very sensitive to the various parameters, and this should make for noisy mixing, unlike the cited reference. This is a very difficult problem, and our analysis is still incomplete. We note that this circuit is a natural second harmonic generator and so sub-harmonic pumping might be advantageous.

Extended discussions with several members of the Russian group who are pursuing this design strengthen our confidence in our conclusions. Nevertheless, our research is still preliminary, and further research is required before any publication. Incidentally, our work on this problem should be relevant to the Josephson junction oscillator.

IV. Publications

The following publications relevant to the grant research appeared in print or were in preparation during the grant period:

1. M.J. Feldman, "Millimeter and Submillimeter Wavelength Device Development (for Radio Astronomy)," in Review of Radio Science 1987 - 1989, edited by G. Hyde (International Union of Radio Science, Brussels, 1990).

2. M.J. Feldman, "Superconducting Electronics" (partial contribution), in Review of Radio Science 1987 - 1989, edited by G. Hyde (International Union of Radio Science, Brussels, 1990).

3. M.J. Feldman, "An Analytic Investigation of the Superconducting Quasiparticle Mixer in the Low Power Limit," IEEE Trans. Magnetics MAG-27, 2646 (1991).

4. A.W. Lichtenberger, D.M. Lea, C. Li, F.L. Lloyd, M.J. Feldman, R.J. Mattauch, S.-K. Pan, and A.R. Kerr, "Fabrication of Micron Size Nb/Al-Al_2O_3/Nb Junctions with a Trilevel Resist Liftoff Process," IEEE Trans. Magnetics MAG-27, 3168 (1991).

5. R.S. Amos, A.W. Lichtenberger, M.J. Feldman, R.J. Mattauch, and E.J. Cukauskas, "Fabrication of NbCN/PbBi Edge Junctions with Extremely Low Leakage Currents," IEEE Trans. Magnetics MAG-27, 3200 (1991).

6. M.J. Feldman, contribution to: "Report of the Heterodyne Submillimeter-Wave Sensors Panel," in Workshop Proceedings: Sensor Systems for Space Astrophysics in the 21st Century, edited by Barbara A. Wilson (Jet Propulsion Laboratory Publication 91 - 24, Vol. 2, Pasadena, California, 1991), pp. 50 - 57.

7. M.J. Feldman, "Millimeter - Wave Detection," solicited article, in the Concise Encyclopedia of Magnetic and Superconducting Materials, edited by J. Evetts (Pergamon, Oxford, 1992) pp. 329-332.

8. Qing Ke and M.J. Feldman, "Source Conductance Scaling for High Frequency Superconductor Quasiparticle Receivers," Proceedings of the Third International Symposium on Space Terahertz Technology, pp. 538-547, March 1992.

9. Qing Ke and M.J. Feldman, "Reflected Power Effects in Computer Simulations Using the Quantum Theory of Mixing," The 1992 IEEE MTT-S International Microwave Symposium Digest, pp. 1425-1428, June 1992.

10. Qing Ke and M.J. Feldman, "Constant Output Noise Temperature of the Superconducting Quasiparticle Mixer," IEEE Trans. Applied Superconductivity 3, 2245 (1993).

11 Qing Ke and M.J. Feldman, "Optimum Source Conductance for High Frequency Superconductor Quasiparticle Receivers;" accepted for publication in IEEE Trans. Microwave Theory Tech., March 1993.

12. M.J. Feldman and M.F. Bocko, "Analysis of the Phase - Sensitive SIS Heterodyne Receiver," in preparation.

13 M.J. Feldman, S.-K. Pan, and A.R. Kerr, "Saturation of the SIS Mixer by Monochromatic and Thermal Signals," in preparation, to be submitted to IEEE Trans. Microwave Theory Tech.

14. Qing Ke and M.J. Feldman, "Reflected Power Effects and High Gain in the Quantum Theory of Mixing," in preparation, to be submitted to IEEE Trans. Microwave Theory Tech.

15. M.J. Feldman and N.G. Ugras, "The Josephson Junction as a Variable Inductance Tuning Element," in preparation.

V. Professional Personnel under Research Grant

Marc J. Feldman, Senior Scientist and Associate Professor
Qing Ke, graduate student

Marc J. Feldman was a member of the Department of Electrical Engineering of the University of Rochester during the period of this research grant. Qing Ke earned a Masters' degree in Physics and a Masters' Degree in Electrical Engineering at the University of Rochester during the period of this research grant (no theses titles). He will likely qualify for a Ph.D. in E.E. in 1995.

VI. Interactions

Marc J. Feldman participated in the following major interactions during the report period:

1. Participated in a study conducted by the Bureau of Business Research of the College of William and Mary to identify the most likely superconductivity-related industrial applications of emerging technologies which may result from the development of CEBAF (the Continuous Electron Beam Accelerator Facility), May - November, 1990.

2. Attended the 1990 Applied Superconductivity Conference, Snowmass, Colorado, September 24-28, 1990, and served as Chair of the session "LTS Microwave Detectors." The following papers were presented:

   2a. "An Analytic Investigation of the Superconducting Quasiparticle Mixer in the Low Power Limit."

   2b. "Fabrication of Micron Size Nb/Al-Al_2O_3/Nb Junctions with a Trilevel Resist Liftoff Process." Co-authors: A.W. Lichtenberger, D.M. Lea, C. Li, F.L. Lloyd, R.J. Mattauch, S.-K. Pan, and A.R. Kerr.

   2c. "Fabrication of NbCN/PbBi Edge Junctions with Extremely Low Leakage Currents." Co-authors: R.S. Amos, A.W. Lichtenberger, R.J. Mattauch, and E.J. Cukauskas.

3. Attended the Fourteenth Annual Western New York Electron Devices Conference, at Rochester Institute of Technology, Rochester, New York, October 31, 1990, with Qing Ke. Ke presented the talk "Frequency Dependence of the Sensitivity of the Superconductor Quasiparticle Receiver."

4. Served on the External Review Panel for the Basic Research Program of the Naval Research Laboratory, Washington D.C., December 7, 1990.

5. Served on the Heterodyne Submillimeter-Wave Sensors Panel of NASA's "Sensor Systems for Space Astrophysics in the 21st Century Workshop," Pasadena, California, January 23 - 25, 1991. The objective of the Workshop was to determine NASA's future requirements for electromagnetic radiation sensor systems, and to recommend a research program for NASA to achieve the required capabilities.

6. Attended the Second International Symposium on Space Terahertz Technology, at the Jet Propulsion Laboratory, Pasadena, California, February 26 - 28, 1991.

7. Attended the Superconducting Digital Circuits and Systems Conference, at George Washington University, Washington, D.C., September 11-13, 1991.

8. Attended the Workshop on Superconductive Electronics: Devices, Circuits, and Systems, Fallen Leaf Lake, California, September 22-26, 1991. Presented the talk "Emergent Properties of SIS Receivers."

9. Attended the Fifteenth Annual Western New York Electron Devices Conference, at Rochester Institute of Technology, Rochester, New York, October 30, 1991, with Qing Ke. Ke presented the talk "Emergent Properties of Optimized SIS Receivers."

10. Attended the Third International Symposium on Space Terahertz Technology, Ann Arbor, Michigan, March 24-26,1992, with Qing Ke, and served as Chair of the session "SIS Theory and Fabrication I." Ke presented the talk "Source Conductance Scaling for High Frequency Superconductor Quasiparticle Receivers," by Qing Ke and M.J. Feldman.

11. Attended the 1992 IEEE MTT-S International Microwave Symposium, Albuquerque, New Mexico, June 1-5, 1992. Presented the talk "Reflected Power Effects in Computer Simulations Using the Quantum Theory of Mixing," by Qing Ke and M.J. Feldman.

12. Attended the Hypres Scientific Advisory Board Meeting, Chicago, Illinois, August 23, 1992. Presented the invited lecture, "Research on LTS Sources and Receivers." Hypres is a small company located in Elmsford, New York, specializing in superconducting electronics.

13. Attended the 1992 Applied Superconductivity Conference, Chicago, Illinois, August 23-28, 1992,with Qing Ke, and served as co-Chair of the session "Mixers." Ke presented the talk "Constant Output Noise Temperature of the Superconducting Quasiparticle Mixer," by Qing Ke and M.J. Feldman.

14. Ke presented the talk "Reflected Power Effects and High Gain in the Quantum Theory of Mixing," by Qing Ke and M.J. Feldman, at the Sixteenth Annual Western New York Electron Devices Conference, Rochester Institute of Technology, Rochester, New York, November 4, 1992.